

**TESTING THE PARADIGM OF ADIABATICITY \***

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We introduce the concepts of adiabatic (curvature) and isocurvature (entropy) cosmological perturbations and present their relevance for parameter estimation from cosmic microwave background anisotropies data. We emphasize that, while present-day data are in excellent agreement with pure adiabaticity, subdominant isocurvature contributions cannot be ruled out. We discuss model independent constraints on the isocurvature contribution. Finally, we argue that the Planck satellite will be able to do precision cosmology even if the assumption of adiabaticity is relaxed.

**1. Introduction**

The cosmic microwave background (CMB) constitutes one of the pillars of modern cosmology. Since the first measurement of primary anisotropies by the COBE satellite<sup>1</sup> in 1992, the steady increasing precision has culminated with the WMAP results<sup>2</sup>.

The dependence of the CMB power spectrum on cosmological parameters is well understood, and fast numerical codes produce a theoretical power spectrum in a few seconds with better than percent accuracy. Therefore the extraction of cosmological parameter by grid or Monte Carlo techniques is now a well established practice. By “cosmological parameters” we mean a set of 5 dimensionless numbers which describe the matter content of the universe today ( $\Omega_\Lambda, \Omega_c, \Omega_b, \Omega_r, \Omega_\kappa$  parameterizing the energy density in terms of the cosmological constant, cold dark matter (CDM), baryons, radiation and curvature, respectively), supplemented with the value of the Hubble parameter today,  $H_0$ , and the optical depth to reionization,  $\tau$ . In the simplest scenario which contains scalar perturbations only, we need two other parameters to describe the amplitude ( $A_s$ ) and spectral dependence ( $n_s$ ) of the initial perturbation spectrum. Certain combination of those parameters constitute “orthogonal sets” with respect to the CMB data, hence can be determined with very high accuracy<sup>3</sup>.

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Combination of CMB data with other cosmological data sets allows to constrain the above 9 standard parameters within a few percent. This is a spectacular achievement, even more so since many totally independent measurements seem to be converging toward the same values<sup>4</sup>. The accuracy of parameter extraction relies on the assumption that the initial conditions (IC) for the perturbations are of the simplest possible type, namely purely adiabatic. It is much more difficult to use the CMB to constrain cosmological parameters and at the same time to learn more about possible deviations from adiabaticity in the IC. Nevertheless the CMB represents the most promising data set to learn about the type of initial conditions realized in the observed Universe: it is our window to the very early universe.

## 2. Adiabaticity and the CMB

We describe the early universe by a mixture of baryons, CDM, photons and massless neutrinos. Entropy perturbations of the mixture are characterized by the intrinsic entropy of each component and a contribution coming from the mixture<sup>5,6</sup>. For perfect fluids, the former vanishes, while the latter is a weighted sum over contributions of the type

$$S_{\alpha\beta} \equiv \frac{\delta_\alpha}{1+w_\alpha} - \frac{\delta_\beta}{1+w_\beta}, \quad (1)$$

for two fluids  $\alpha, \beta$ , where  $\delta_x \equiv \delta\rho_x/\rho_x$  is the energy contrast and  $w_x \equiv P_x/\rho_x$  is the equation of state parameter for species  $x$ . A non vanishing  $S_{\alpha\beta}$  corresponds to fluctuations in the number density ratio of the two species. If these perturbations of the entropy are such that the total density is initially unperturbed, they are termed isocurvature initial conditions (IC). CDM isocurvature IC excite a sine oscillation in the photon-baryon fluid<sup>7</sup>, this corresponds (for a flat universe) to a first peak in the temperature CMB power spectrum at a multipole  $\ell \approx 110$ .

The simplest choice for IC is the one in which there is no fluctuation in the relative number density of the species, hence no entropy perturbations:

$$\frac{\delta\rho_b}{\rho_b} = \frac{\delta\rho_c}{\rho_c} = \frac{3}{4} \frac{\delta\rho_\gamma}{\rho_\gamma} = \frac{3}{4} \frac{\delta\rho_\nu}{\rho_\nu} \quad (\text{Adiabatic}).$$

Those IC are termed adiabatic. They naturally arise from 1-field inflationary scenarios, which have only one degree of freedom, and therefore cannot produce entropy fluctuations. Adiabatic IC can be described in terms of the induced curvature perturbation  $\zeta$ , which in longitudinal gauge is related to the energy-density contrast  $\delta$  by

$$\zeta = \left( -\frac{3}{2} \frac{\mathcal{H}^2}{k^2} + \frac{1}{3(1+w)} \right) \delta. \quad (2)$$

Adiabatic IC excite a cosine oscillatory mode, which induces a first peak at  $\ell \approx 220$  (for a flat universe) in the CMB angular power spectrum. The observation of the first peak<sup>8</sup> at  $\ell = 220.1 \pm 0.8$  has substantially confirmed the domination of adiabatic

IC. However, a subdominant isocurvature contribution to the prevalent adiabatic mode cannot be excluded.

Beside AD and CDM isocurvature, the complete set of IC for a fluid consisting of photons, neutrinos, baryons and dark matter in general relativity consists of three more modes<sup>9</sup>. These are the baryon isocurvature mode (BI), the neutrino isocurvature density (NID) and neutrino isocurvature velocity (NIV) modes. Those five modes are the only regular ones, i.e. they do not diverge at early times. The NID mode can be understood as a neutrino entropy mode, while the NIV consists of vanishing density perturbations for all fluids but non-zero velocity perturbations of the neutrinos. Each mode can have a different spectral index, and cross-mode correlations can be either positive or negative<sup>10,11</sup>.

Initial conditions which represent a (anti-)correlated mixture of the adiabatic and the CDM isocurvature mode are obtained *e.g.* in the curvaton model<sup>12,13</sup>. WMAP constraints for the curvaton model have been derived for the case of CDM and baryons isocurvature fluctuations<sup>14</sup>. The NID mode can be generated from perturbations of the neutrino chemical potential<sup>15</sup>, and bounds have recently been derived for this case<sup>16</sup>. It seems more difficult to produce a NIV mode: a working model is at present still lacking.

### 3. Model-independent constraints

In order to test the paradigm of purely adiabatic fluctuations we now allow for general isocurvature contributions and derive bounds on their amplitudes and spectral index from CMB and large scale structure data<sup>11</sup>. Although independent of any model for the generation of perturbations, this approach has the disadvantage of introducing many new free parameters in the description of the power spectrum. To reduce this number somewhat, we assume the same spectral index for all modes. Since the current CMB data are in excellent agreement with purely adiabatic IC, it is not surprising that there is no statistical evidence that such extra parameters should be non-zero. Occam's razor would therefore dictate to stick to the simplest adiabatic description, lacking any evidence for a more complicated model. However, there is no compelling reason why the physics of the early universe should boil down to only one degree of freedom.

A second reason why model-independent constraints should be regarded with care is that in any specific implementation some of the parameters will be correlated. For instance, in the curvaton scenario, adiabatic and residual isocurvature modes are always totally (anti)correlated. Therefore not only the number of extra degrees of freedom is reduced, but the parameter space of the model is a possibly highly constrained subspace of the model-independent parameter space.

This phenomenological approach gives useful hints on the “stiffness” of current data, and indeed the possibility of accommodating isocurvature modes has been considerably reduced by WMAP<sup>17</sup>. However, large degeneracies between isocurvature modes and cosmological parameters still allow for relatively high isocurvature

contribution<sup>18,19</sup>. The exact amount depends on the type of isocurvature mode considered and on how many of the 5 fundamental modes are allowed for at the same time.

#### 4. Initial conditions independent constraints

With present data it is difficult to constrain at the same time both the IC and the cosmological parameters using CMB alone. A more powerful approach is to include data on the matter power spectrum<sup>11</sup>, or “priors” on the cosmological parameters coming from other observations<sup>19</sup>. The future high accuracy measurements of CMB polarization will give a substantial help in breaking degeneracies between IC. The degeneracies in the parameter dependence of temperature and polarization are almost orthogonal, and polarization can therefore lift “flat directions” in parameter space.

To determine cosmological parameters independently on the IC, one includes general isocurvature modes, and then marginalize over them. Bucher and collaborators<sup>20</sup> considered forecasts for WMAP and Planck, and concluded a few years ago that such a procedure would make it effectively impossible to constrain parameters with meaningful precision. This result was based on a set of cosmological parameters which has been shown to lead to large overestimates of the expected errors<sup>3</sup>. We have reproduced their study, using an improved Fisher Matrix technique as in Rocha *et al.*<sup>21</sup>. In particular, we give forecasts not for the highly degenerate directions defined by the cosmological parameters, but rather for orthogonal combinations which are well measured by the CMB. Along this directions forecasts are much more reliable. The main features are shown in Fig. 1. There we plot the expected  $1 - \sigma$  error in percent for 6 quantities which are directly probed by the CMB (see figure caption).

For WMAP, marginalization over general initial conditions will indeed give errors which for all quantities will be roughly a factor 10 larger than in the purely adiabatic case, when temperature information alone is considered (cf first and third bar in the left panel). When the full polarization information is included, the errors will still be within approximately 10 to 30% even in the general isocurvature scenario. From the right panel, we deduce that for the Planck experiment<sup>22</sup> the worsening of the errors will be much less if the high quality polarization information is included. Roughly, including isocurvature modes we expect errors which are larger than in the adiabatic case by about a factor of 2, but mostly still within the few percent accuracy.

This shows that the CMB alone will be able to provide high precision cosmology even if the strong assumption of purely adiabatic initial conditions will be relaxed. Combining CMB results with other observation which independently constrain the cosmological parameters, will enable us to fully open this window to the mysterious epoch of the very early universe.

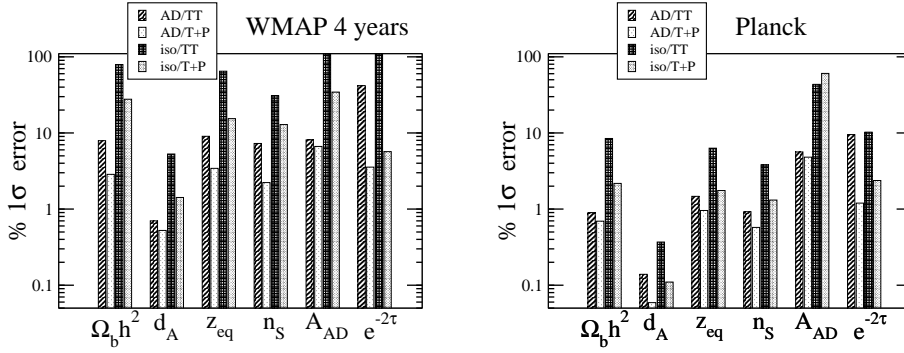


Figure 1. Fisher Matrix forecast for the percent  $1 - \sigma$  errors on 6 quantities which are well determined by CMB alone. The left (right) panel is a forecast for WMAP 4 years mission (Planck). From left to right, on the abscissa axis: the baryon density,  $\Omega_b h^2$ , the angular diameter distance  $d_A$ , the redshift of matter-radiation equality  $z_{eq}$ , the scalar spectral index  $n_s$ , the scalar adiabatic amplitude  $A_{AD}$  and a function of the optical depth to reionization,  $\tau$ . In the legend, “AD” means that only adiabatic fluctuations were included, “iso” means that general isocurvature modes were included and marginalized over. “TT” includes temperature information alone, “T+P” has temperature, E-T correlation and E-polarization.

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